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Final Design Report For:

THIRD GENERATION DESIGN SOLAR CELL MODULE
LSA TASK V, LARGE SCALE PRODUCTION

DATE OF PUBLICATION: AUGUST 1980

JPL CONTRACT NO. 955409

APPROVED BY: K. S. Ling

APPLIED SOLAR ENERGY CORPORATION
15251 EAST DON JULIAN ROAD
CITY OF INDUSTRY, CA. 91745

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ABSTRACT

During this contract solar cell modules were designed and built in accordance with the JPL Document No. 5101-16 Revision A, entitled" Block IV Solar Cell Module Design and Test Specification for Intermediate Load Center Applications. A total of twelve (12) preproduction modules were constructed, tested and delivered. A new concept to the frame assembly was designed and proven to be quite reliable. This frame design, as well as the rest of the assembly, was designed with future high volume production and the use of automated equipment in mind.

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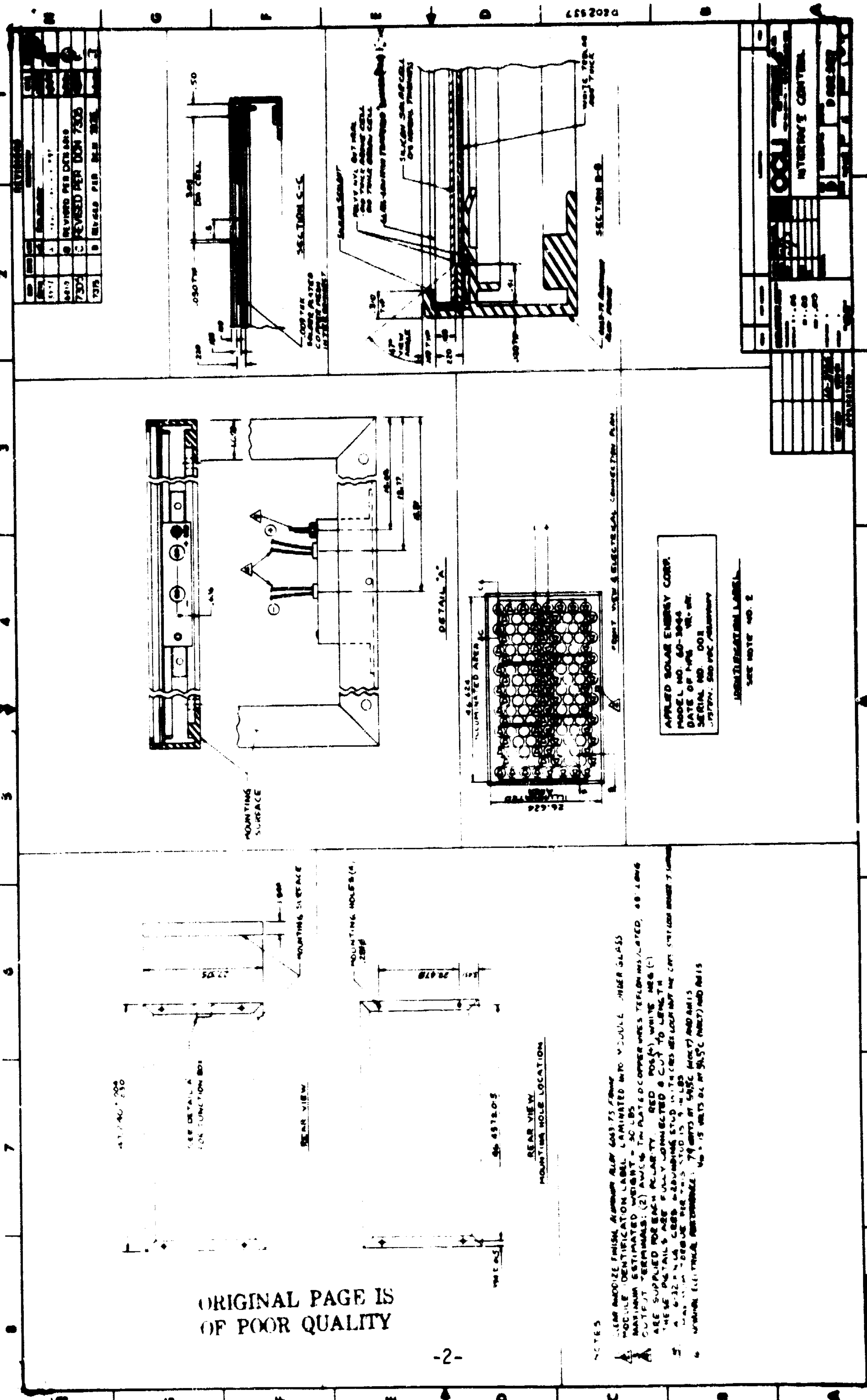
1.0 INTRODUCTION

The objective of this program was to design, fabricate, acceptance test, and evaluate eleven (11) pre-production modules complying with the requirements of JPL Document No. 5101-16, Revision A, entitled "Block IV Solar Cell Module Design and Test Specification for Intermediate Load Center Applications", dated 1 November 1978. The total output of the eleven (11) modules was to be in excess of 800 watts of peak power at AM1.5 and nominal operating cell temperature (NOCT). During this contract, modifications were made which resulted in variations of the number of modules and total power requirements. The first revision was from eleven (11) modules to ten (10), with a total power increase from 800 watts to 900 watts. This was a result of module modification that will be discussed later. The final number of modules was changed to twelve (12) due to power variations affected by a higher than calculated nominal operating cell temperature (NOCT).

In addition, ASEC prepared a standarized price estimate using samics for 10,100, and 1000, kilowatts of solar modules.

2.0 TECHNICAL DISCUSSION

The module designed and constructed during this contract met all of the design requirements of JPL Document No. 5101-16 - Revision A, dated 1 November 1978. It consisted of a glass superstrate, aluminum frame, PVB encapsulated assembly and white Tedlar backing. A further discussion will be made of each specific area in the following paragraphs. An overall view of the design can be seen in Drawing No. D-202557.



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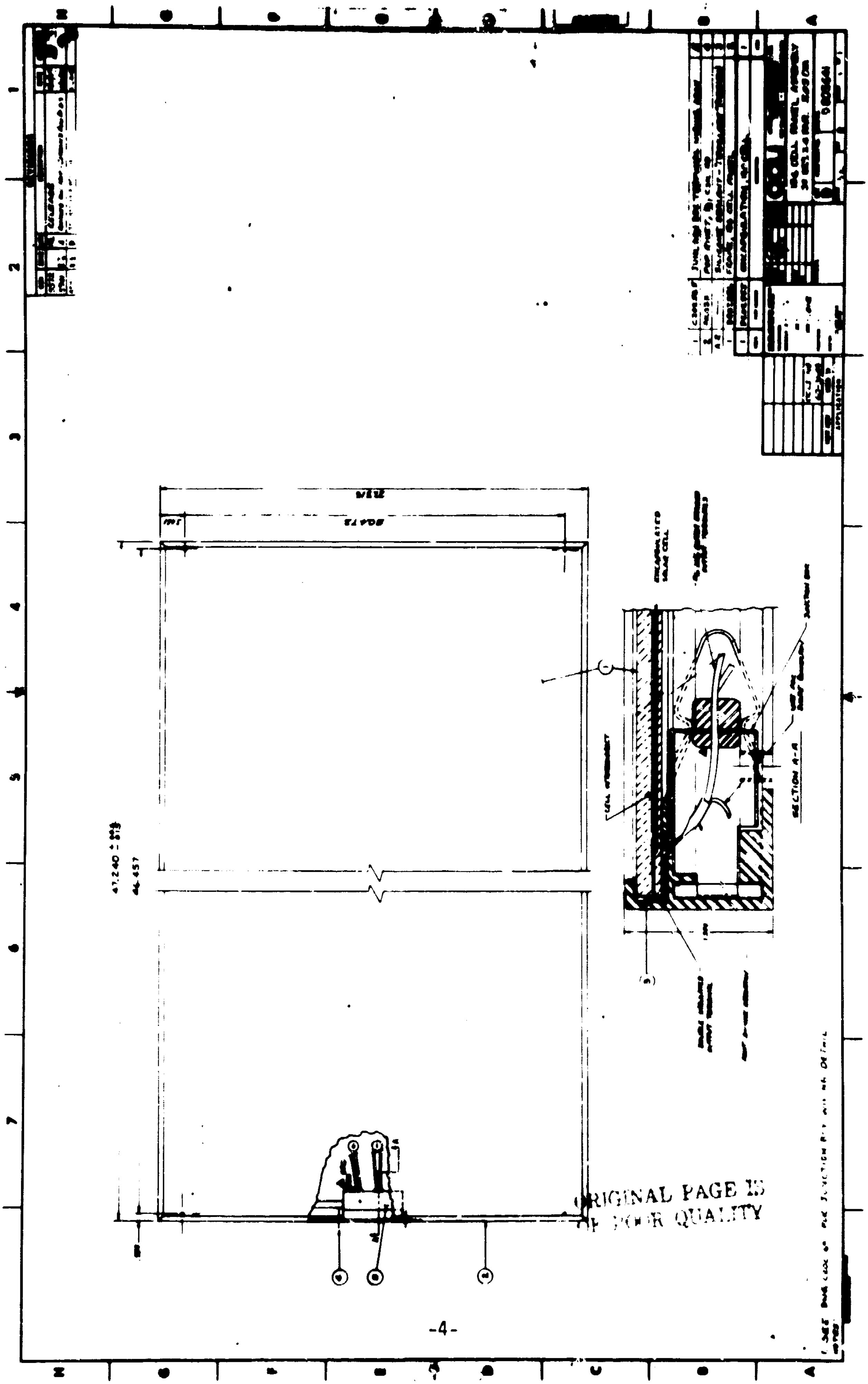
2.1 Module Design

The preliminary module design had overall dimensions of 21.91" x 47.24" x 1.19". It consisted of a piece of 3/16" thick Sunadex glass, an aluminum frame, solar cells, polyvinyl butyral for encapsulation, "Proglaze" for edge sealing, Tedlar film for moisture barrier, and the necessary electrical terminals. Each module was to have (120) 2.95" round solar cells. This module design utilized cells connected, 4 in parallel and 30 in series, which was adequate to operate at 15 volts at 28°C. At NOCT which was estimated to be approximately 48°C, the number of cells in series was insufficient. Our understanding was that the module would be intended for intermediate load center applications, the system voltage would probably be 500 V.D.C. in which case 36 of the proposed modules connected in series will supply the required voltage. The V_{NO} of the Preliminary module design would provide 13.9 volts, inadequate for the intermediate load center applications.

The original module power output analysis was optimistic. But the analysis indicated that using 16% efficiency cells, the module output would be 14%, (83.1W/72.73W = 1.14 times higher than was required to provide the 800 watts with eleven modules). ASEC was confident that the program requirement would be met. After the preliminary design review, it was determined, however, that modifications were necessary. To satisfy the requirement (V_{NO}) of 15 V.D.C. or a convenient fraction or multiple of 15 V.D.C., the module for this program had to be re-designed. The original design would not provide V_{NO} of 15 V.D.C. at NOCT. In the revised module design, as can be seen in Drawing No. D-805641, No.202557, and No.202555, the new overall dimensions are 27.38" x 47.24"


SECTION A-A

x 1.544". The cell configuration was changed so each module had (136) 3.05" diameter solar cells, connected four in parallel and thirty-four (34) in series.

The redesign required a complete review of all components. For example, the 3.05" diameter cell was necessary to provide the best packing factor within the JPL established module dimensions, and still comply with the power requirements. An additional design change was decided on, following completion of test program which consisted of changing from annealed glass to tempered glass in order to avoid the possibility of cracking due to temperature differences in field use. The shadowing effect causes the perimeter of the glass to be cooler than the center. This in turn puts the edges in tension due to the greater thermal expansion in the center. When this difference is great enough, annealed glass will crack. This change was based on actual data from the field where it was determined that annealed glass failed when the edges were shadowed by the frame. In the following paragraphs each component will be discussed, including the revisions that were made.

2.1.1 <u>Solar Cell</u>

The original size of the solar cell was 2.95" in diameter. It was reduced from the standard 3" diameter so 120 cells would fit within the maximum module dimension of 1.2 meters (47.244 inch). The bulk silicon was Czochralski grown, boron doped, P-type single crystal with a nominal resistivity of 10 ohm-cm. The wafers were chemically polished. The junction was formed by thermal diffusion using $POCl_3$ as the source material. Aluminum was printed on and alloyed into the P-side of the

wafer forming a back surface field (BSF)to increase the electrical output. Evaporated and sintered titanium-palladium-silver was applied to the P and N contacts. The N-contact and the grid pattern were generated by the photoresist technique. A dual layer antireflective coating was applied to the active surface of the cell to minimize the reflection loss. The cell fabrication sequence is shown in Flow Chart I. The cell size had to be changed during the module redesign phase from this 2.95" diameter to the nominal size of 3.05" in diameter. The 3.05" diameter cells would provide the best packing factor (using round cells) within the specified maximum module dimension of 1.2 meters (47.244 inch). This cell is shown in Drawing No. A2021554. The process and material remained the same as described above.

The first cells fabricated had an electrical distribution for 136 cells as follows:

AVERAGE EFFICIENCY AT 28°C	NO. OF CELLS
15.41%	16
15.61%	41
15.82%	45
16.03%	34

Disregarding mismatch and interconnecting losses, the weighted average of the 136 cells was 15.76% at AM1 and 28°C. In addition to the individual testing, the cells were re-measured after the interconnect was soldered to the N-contact. The testing voltage was increased from 487 mV to 495 mV to compensate for the difference between the estimated voltage temperature coefficient of -2.4 mV/°C and the measured value of -2.6 mV/°C. The measurement was performed at the end of the

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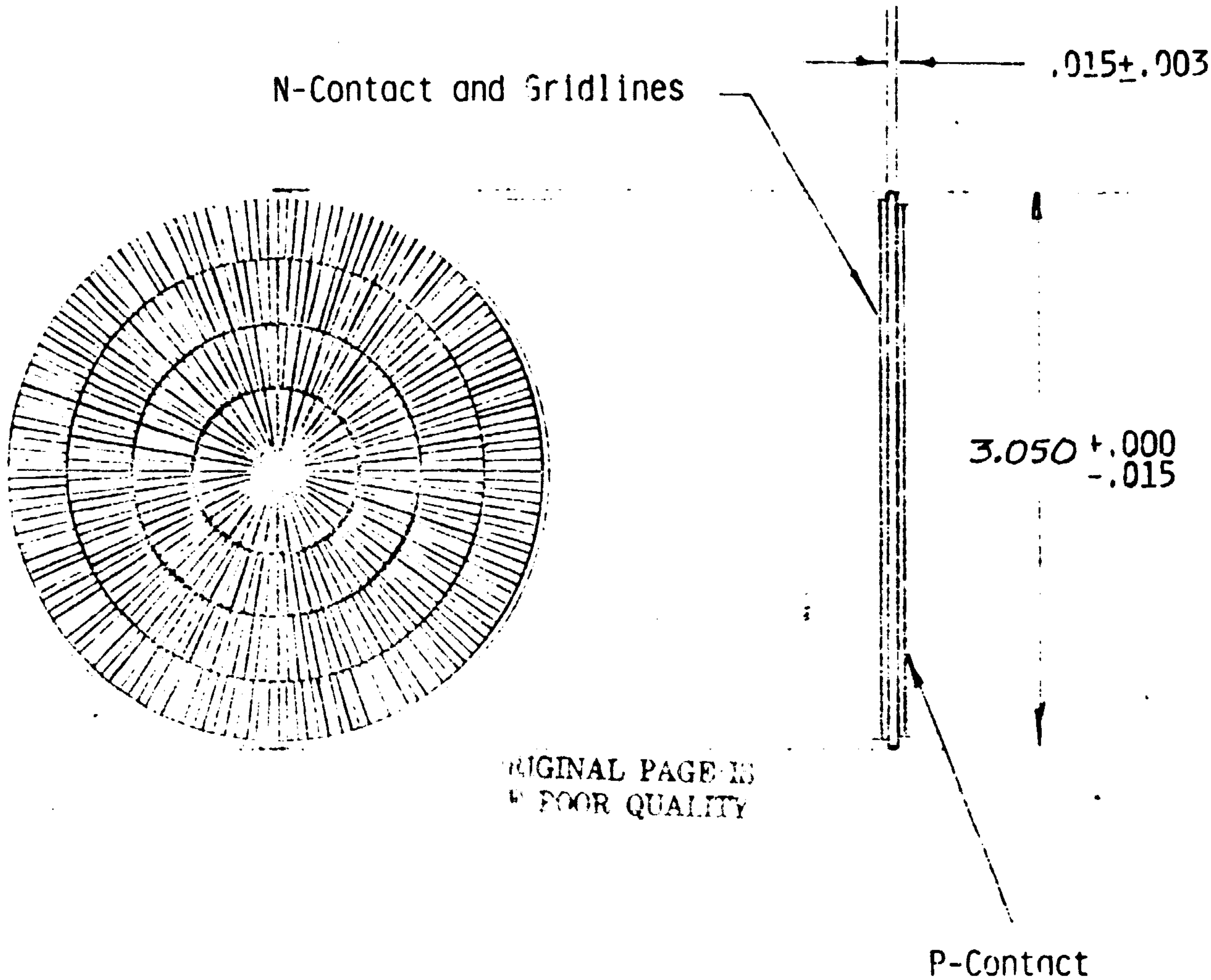


FIGURE 3

1.0 N-Contact of .25 diameter is at center of cell.

2.0 Both contact-metals are vacuum deposited titanium-palladium-silver.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES	DRAWN	S. Anpappone	6/4/79
TOLERANCES:	CHECK	W J S	8/9/79
DECIMALS .X ±	ENGR	S. Kolpanone	6/4/79
.XX ±	PROD		
.XXX ±	QA		
FRACTIONS ±	MATERIAL	Silicon Solar Cell	
ANGLES ±			
DO NOT SCALE DRAWING			

OCLI — OPTICAL COATING LABORATORY, INC. PHOTOELECTRONICS GROUP
15251 Don Julian Rd • City of Industry, Calif. 91746

HIGH EFFICIENCY 3.050' DIAMETER TERRESTRIAL CELL

SIZE	CODE IDENT NO	DWG NO
A		A-202554
SCALE	REV	SHEET OF

FLOW CHART I

CELL FABRICATION

1. Grow ingot
2. Grind ingot
3. Slice into wafers
4. Clean and chemically polish wafers
5. Deposit diffusion mask
6. Diffuse wafer to form junction
7. Remove diffusion oxide and mask
8. Apply aluminum to P-side
9. Alloy aluminum to form back surface field
10. Clean wafers for contact application
11. Deposit P-contact materials (Al, Ti-Pd-Ag)
12. Generation of N-contact and gridlines using photoresist technique
13. Deposit antireflective coating
14. Sinter contacts and AR coating
15. Inspect for mechanical defects
16. Test for electrical output
17. Transfer to module fabrication

interconnect to include any I^2R drop through the interconnect. This additional testing was performed to verify electrical output after attachment of the interconnect. Each string of 17 cells was also measured to assure that no low output strings were assembled into the module. The result of this testing allowed us to determine the selection and matching of cells and cell strings, and set up a guideline for further module production. Due to the consistency found during this testing, it was determined that the individual cell strings would not have to be measured if the cells within a string were equally balanced and the total module strings were evenly grouped.

2.1.2 Superstrate

Originally ASEC chose 3/16" thick annealed, edge-ground Sunadex glass as the superstrate mainly due to the results published in JPL Report 5101-62 entitled, "Photovoltaic Solar Panel Resistance to Simulated Hail". Annealed glass upon impact would only crack but the module would still function with very small electrical degradation. Tempered glass would shatter upon impact resulting in loss of power. Even though the mechanical strength of the annealed glass is less than that of the tempered glass, the 3/16" thickness is more than sufficient to satisfy the hail test requirement. Because grinding the edges of the glass improves the performance of the steel ball drop test, ASEC decided to use edge-ground glass superstrate.

Although the annealed glass module passed the qualification tests, subsequent tests and a review of related field test data indicated that the annealed glass might not withstand the expected temperature differences.

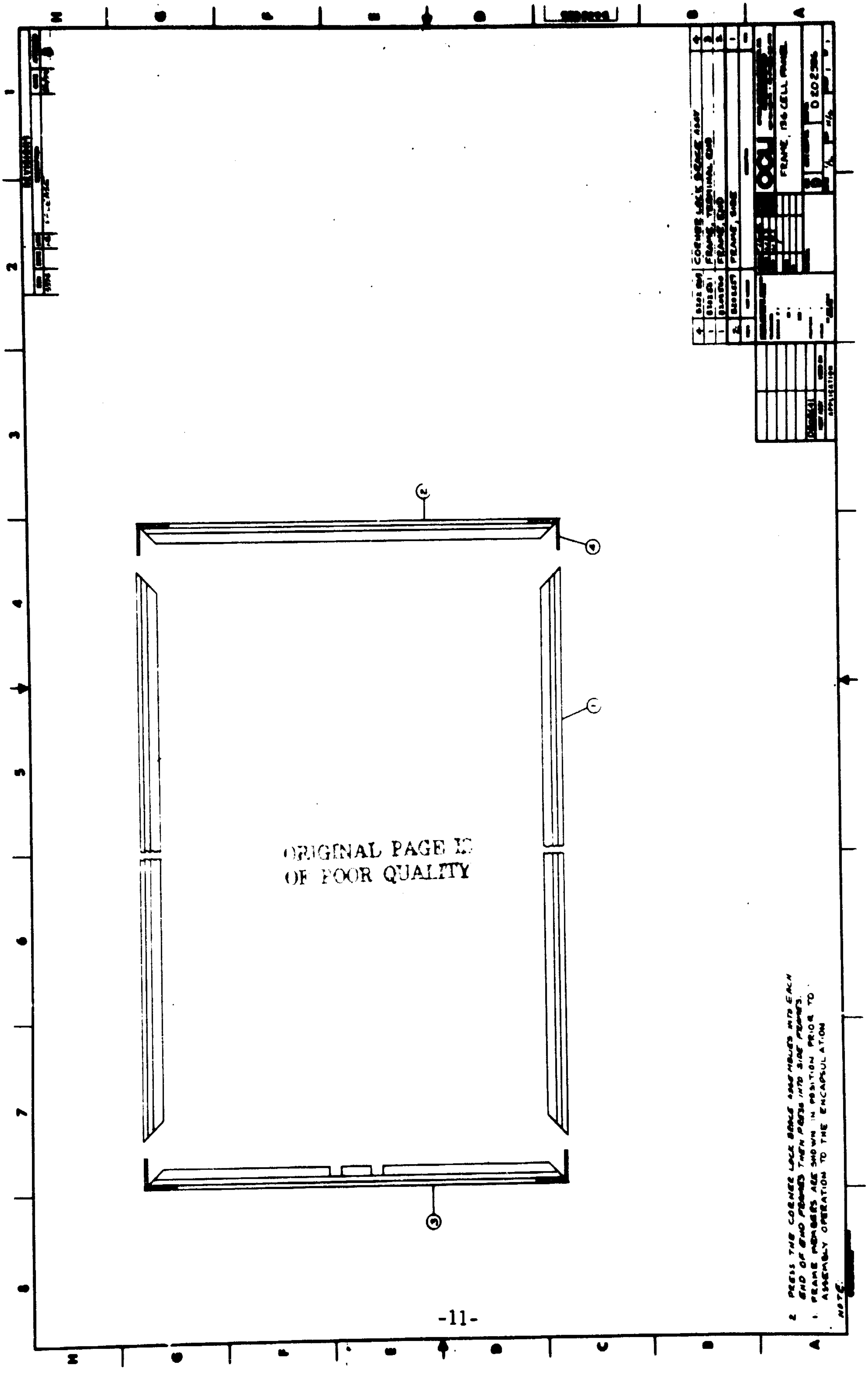
The superstrate was therefore changed to tempered sunadex glass.

2.1.3 Frame

The frame is an extrusion made of 6063-T5 aluminum alloy. After the drawings were submitted, a meeting was held between ASEC engineering and JPL Stress Analysis Engineer to discuss the adequacy of extrusion design. It was concluded that a modification was required. In order to maintain the low profile that was desired, various sections were modified to increase strength, but maintain low cost. The new design was presented at the Preliminary Design Review. All drawings having a cross-section of the extrusion have been revised. JPL suggested that ASEC should look into a possible drainage problem in the extrusion, so a drain hole was added to the frame in the junction box area. The extruded members are interlocked with spring-loaded corner braces to provide a picture frame configuration as shown in Drawing No. D-202556. This concept of low cost assembly is widely used in the window and screen industry. All of the frame components are anodized for corrosion resistance. Four (4) 0.281" diameter clearance holes were provided in the bottom flange for module mounting.

2.1.4 Interconnect

The interconnects were made of 5 mil thick, 3/16" wide, annealed copper mesh. Interconnects are solder-plated to eliminate the necessity of adding solder during the assembly operation. The cross-section of the interconnect has been computed to carry the maximum current that might flow through the module with minimal losses. Mesh openings will provide stress relief over the operating temperature range, and improve the shadow effect of interconnect over cell. Our cell design provided for



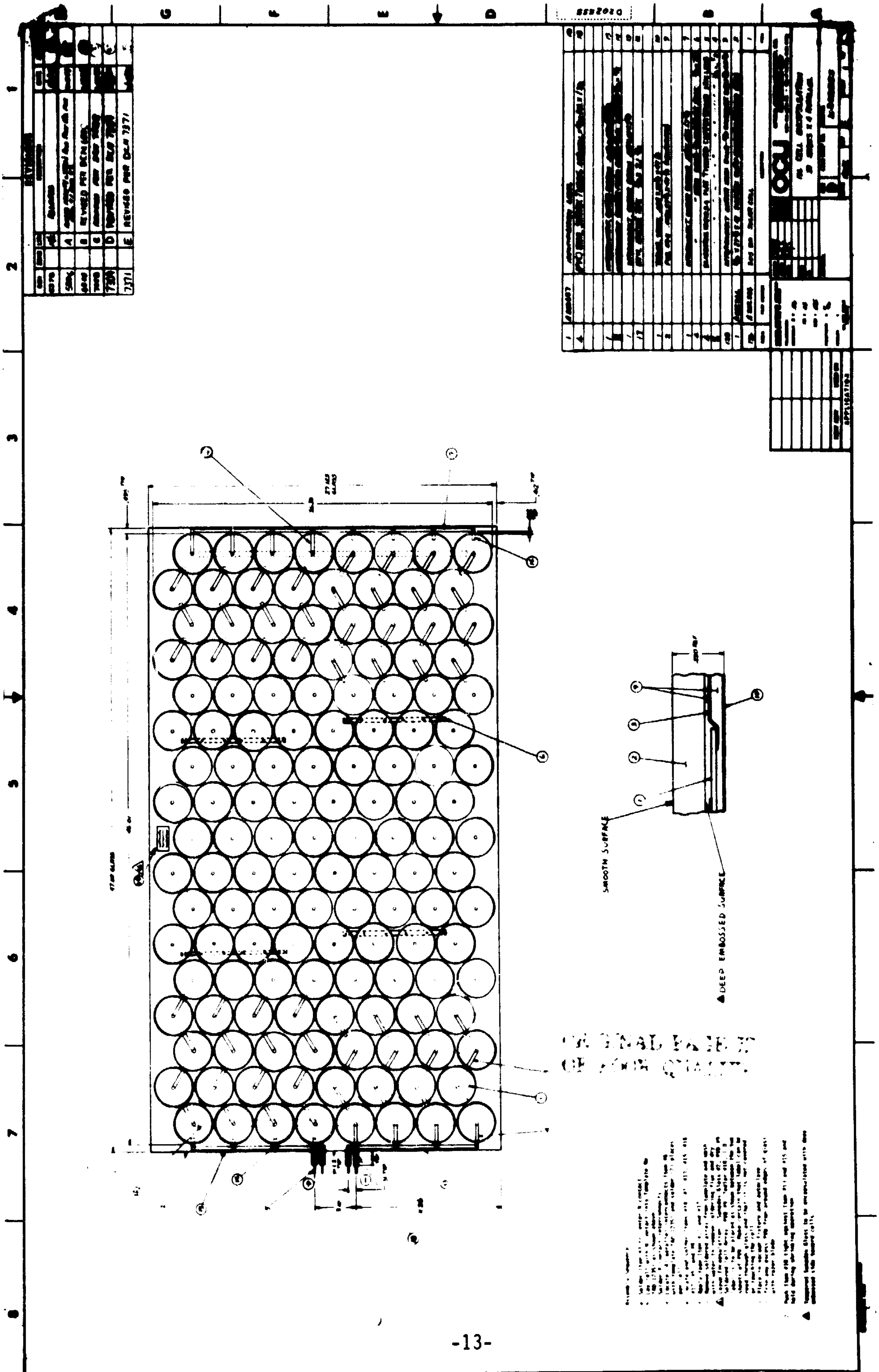
single point connection of interconnect at the center (on the top "N" side), and about 1/2 inch of contact on the bottom "P" side. The central point contact provides a redundancy feature inasmuch as all current is collected at this center point. Because the width of the mesh will span any crack through this central region, it naturally provides redundancy on either side of such a crack.

2.1.5 Cell Assembly

The cell assembly, as shown in Drawing No. D-202555 consists of (136) 3.05" diameter cells connected four (4) cells in parallel and thirty-four (34) cells in series. To enhance reliability of the module, four cells in every sixth row from each end were connected in parallel on the P-side. This design configuration provides six (6) series blocks. The design was chosen to meet the power output, and the physical module dimension requirements. It was necessary to connect thirty-four (34) cells in series, in order to meet the 15 V.D.C., and NOCT requirement. As mentioned earlier, the 3.05" diameter cell was the optimum size to fit within the 1.2 meter maximum dimension, and a width dimension within the 20mm increment restriction. This design has a somewhat lower than desired (76.8%) packing density, but chosen because of the cost and material savings associated with round, rather than shaped, cells.

2.1.6 Encapsulation

The interconnected 136-cell assembly was laminated between the superstrate and the (4 mil) white Tedlar backing with two sheets of clear (.015" thick) polyvinyl butyral material. Because of the availability, PVB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SMOOTH SURFACE
DEEP EMBOSSED SURFACE
APPLICATION

was used for this program instead of the proposed ethylenevinyl acetate. The white Tedlar was chosen over Mylar because of its moisture resistance property, and the color eliminates the need to apply white paint. The white color is necessary to realize the electrical enchancement discovered by General Electric under JPL/DOE contracts. The 136 cell assembly was measured before and after encapsulation in the ASEC large area simulator, the electrical gain due to the white Tedlar and the Sunadex glass is 6.56%, reasonably close to the earlier estimate of 7%. This encapsulated assembly is shown in Drawing No. D202555.

All of the lamination process was performed in an autoclave using heat, vacuum, and pressure. We feel that the pressure is a necessity to achieve a satisfactory bond between the laminate materials. This type of encapsulated asembly is designed for a twenty (20) year life, and has been fairly well proven with over twenty (20) years of success in a similar application with the automobile industry.

2.1.7 Edge Sealing

A commercial silicone sealant named "Proglaze", which has been in use in the construction industry for many years, was selected as the edge sealant. It remains elastic at low temperatures, eliminating the possibility of cracking the glass superstrate. This material has proven itself in the outdoor environment, with uses in construction, and ASEC has tested it for its sealing and thermal cycling properties. We have found it to be superior to any that we have tried.

2.1.8 Electrical Terminals

The electrical terminals are two (2) Teflon insulated wires (48" long) for each polarity, secured by strain relief mounted in the junction box and attached to the aluminum frame. A 6-32 stainless steel stud was attached to the junction box as a grounding terminal. A 6-32 CRS nut and lock washer was provided to secure the wire on the grounding stud. A bypass diode was connected across the "N" and "P" wires inside the junction box for module protection. This pigtail style of electrical termination was chosen because of lower cost, and the ease with which pre-production modules like these can be tested and connected.

3.0 MODULE TEST ANALYSIS

3.1 Electrical Performance Objective

Each module had (136) 3.05" diameter solar cells connected four in parallel and thirty-four(34) in series. The average efficiency of the cell was estimated to be 16% at AM1.5 and 28°C. The following analysis is somewhat optimistic as the losses due to series resistance and cell mismatch are not included.

(a) Cell Area = $(3.05")^2(2.54\ cm/in)^2 = 47.1\ cm^2$

(b) Cell Output = $47.1\ cm^2 \times 16\% \times 0.1\ W/cm^2 = 0.753$ Watt

(c) Module Output at 28°C including 7% gain from the Sunadex Glass and the White Tedlar = $136 \times 0.753\ W \times 1.07 = 109.6$ Watts

(d) The temperature co-efficient of the module is estimated to be $-0.0046/^{\circ}C$ and the NOCT is estimated to be 48°C. Module output at NOCT = 99.5 watts.

(e) Module current at 15 V and NOCT = =6.63 Amps

(f) Module Area = $27.375" \times 47.244" \times (2.54\ cm/in)^2 = 8343.9\ cm^2$

Module efficiency at NOCT = = 11.9%

(g) Packing Factor = = 76.8%

This analysis was used to establish a guideline for module construction. The actual test results and module performance will be discussed in the following paragraphs.

3.2 Electrical Test Data

A considerable amount of time has been spent during this contract to establish consistent test results that correlate. It was determined that the ASEC large area solar simulator (LASS) was not uniform enough for a module of this size, so our testing was performed in natural sunlight. The measurements in natural sunlight did not, however, correspond with JPL's pulse xenon testing. The following discussion will summarize the findings and comment on some recommendations.

The first module (Serial No.001) fabricated had a power output of 80.3 watts at 15 volts, and 48^{o}C when tested at JPL, which was lower than expected. Because of this, the module was measured three (3) times, in the ASEC parking lot, under the JPL pulsed xenon simulator, and at Table Mountain. Reference Cell No. 436 was used for all the measurements. The power varied from 80.3 watts as a low to 91.4 watts at the highest, all were corrected to 48^{o}C and 100mW/cm^2. The second module (serial No.002)was tested twice on 13 December 1979 in natural sunlight at the Table Mountain facility. It was very close in comparison to the first module, but had a slightly higher power output.

The first test was conducted with the module temperature held at close to ambient temperature as possible. The second test was run after the

module was allowed to reach its own stabilization temperature in the sun. Power output results have been corrected to NOCT (48°C estimated) and are as follows: Module No. 002 had an output of 88.5 watts at 48°C and 15 V.D.C. when tested near ambient. Module No. 002 output was 85.9 watts at 48°C and 15 V.D.C. when tested at its stabilized temperature. The difference of approximately 2 watts can be explained by slight variations in temperature and in taking data from the I-V curve. The same module when checked at JPL was 75.9 watts, and 76.2 watts respectively. As can be seen in these two examples, there was about 8.8% variation between sunlight and pulse xenon testing. This discrepancy started an investigation into the problem. After some time, it was determined that the response time of our cell was slow enough, apparently due to the back surface field,that the rapid pulsed light on the JPL simulator did not give an accurate measurement. Because of this, JPL changed their testing procedure to a point by point type of plot, where the voltage is fixed, and a current reading (point) is taken. These new measurements are closer to the natural sunlight readings. For a complete review of all test results, see Table 1.

3.3 NOCT

Prior to the qualification testing by JPL, the nominal operating cell temperature (NOCT) was estimated to be 48°C. We felt that our figures were conservative using this estimate, but after actual testing at JPL, the NOCT was determined to be 54.5°C. All power output figures will therefore reflect the 54.5°C NOCT.

3.4 Electrical Performance Testing

The following data was derived during actual testing. Single cells were tested and grouped using an XT-10 solar simulator. The distribution of 136 cells was as follows:

AVERAGE EFFICIENCY AT 28°C AND 100mW/cm^2	NUMBER OF CELLS
15.51%	16
15.61%	41
15.82%	45
16.03%	34

Disregarding mismatch and interconnection losses, the weighted average of the 136 cells was 15.76% at AM1 (100mW/cm^2) and 28°C.

The module testing was performed using the following criteria:

TEMPERATURE/VOLTAGE COEFFICIENT = -0.0026 V/°C (Cell)

= +0.0884 V/°C (Module)

TEMPERATURE/CURRENT COEFFICIENT = 0.015 mA/cm^2/°C (Cell)

= .0028 mA/cm^2/°C (Module

Under these conditions the average power per module (PAVG) was 79 watts. This power was somewhat lower than expected. The major difference was due to a shift from the maximum power point. This shift was a result of higher than calculated NOCT (48°C calculated/54.5°C actual) and the fixed voltage (V_{NO} = 15 volts) requirement. At NOCT

($54.5^{o}C$) and the maximum power point (voltage at 13.8 volts) average module power (Pmax) is approximately 85 watts.

3.4.1 Module Efficiency

Based on Pavg = 79 W at NOCT ($54.5^{o}C$) and Vno (15 volts) the module efficiency is as follows:

MODULE SIZE: 27.357" x 47.240" x $(2.54)^2$ = 8343 cm^2

Pavg = 79 W

$$\text{MODULE EFFICIENCY:} \quad = \frac{79W}{(8343\ cm^2) \times (.1w/cm^2} = 9.5\%$$

Based on Pmax at NOCT ($54.5^{o}C$) the module efficiency is as follows:

$$\frac{85\%}{(8343\ cm^2)(0.1W/cm^2)} = 10.2\%$$

3.4.2 Encapsulated Cell Efficiency

Average encapsulated efficiency at NOCT ($54.5^{o}C$ and Vno 15 volts) is as follows:

$$\frac{79W/MODULE}{136\ CELLS} = .5809W/Cell$$

$$\text{CELL AREA} = 47.1cm^2$$

$$\text{EFFICIENCY} = \frac{.5809\ W/CELL}{(42.1cm^2)(0.1W/cm^2)} = 12.3\%$$

Average encapsulated cell efficiency at NOCT ($54.5^{o}C$ and 13.8 volts) = Pmax

average power at NOCT.

$\frac{85W}{}$ = .625 W/CELL

136 CELLS

$$\text{EFFICIENCY} = \frac{.625}{(47.1)(0.1)} = 13.3\%$$

Average encapsulated cell efficiency at $28^{o}C$ and Pmax:

Pmax @ NOCT and 13.8 Volts = 85W or Pmax is taken at 13.8 Volts and 6.1594 Amps.

$\Delta T = 54.5^{o}C - 28^{o}C = 26.5^{o}C$

Voltage Temperature Coefficient = .0026V/Cell/^{o}C

Voltage Corrected to $28^{o}C$:

34 Cells x .0026V/Cell/^{o}C x $26.5^{o}C$ = 2.3426 Volts

13.8 + 2.3426 = 16.14 Volts = Power Point Voltage at $28^{o}C$

16.14 Volts x 6.1594 Amps = 99.43W

Pmax at $28^{o}C$ and $100mW/cm^2$ = 99.4W

$$\text{Power}/\text{Cell} = \frac{99.4W}{136\text{ Cells}} = 731W/\text{Cell}$$

$$\text{Efficiency} = \frac{.731W/\text{Cell}}{(47.1cm^2)(0.1mW/cm^2)} = 15.5\%$$

3.5 Module/High Voltage - Ground Continuity

All the modules were also subjected to a high voltage insolation test. The test consisted of a high voltage, (not greater than 500V/sec. up to 2000 Volts), applied between the ground stud and the shorted output terminals. This voltage was then held at the 2000V.D.C. for one (1) minute. During the test, the leakage current was measured and could not exceed 50 microamps. All of the modules passed this test prior to shipping. The actual leakage was between 18 and 20 microamps on all modules. During the JPl qualification testing, there was, however, some high voltage leakage (on module No. 004 and 005) immediately after humidity cycling. We feel confident that this was the result of an improper insulating bushing between the diode and diode bracket. The insulator was of a moisture absorbing material, rather than the phenolic base material that was specified. This was corrected by insuring that the proper insulator is used and by removing the incorrect one from our stock.

All modules have also gone through a good continuity test prior to shipping. The purpose of the test was to insure that all metallic parts, (frame, junction box, grounding stud, etc.), are well grounded. The test was performed using a constant current generator to pass a current through the entire frame structure. Various points were checked between the ground stud and frame. The module was not accepted if the resistance was greater than fifty (50)milliohms. See Figures 1 and 2 for a schematic representation of this test set-up.

3.6 Module Testing/Mechanical

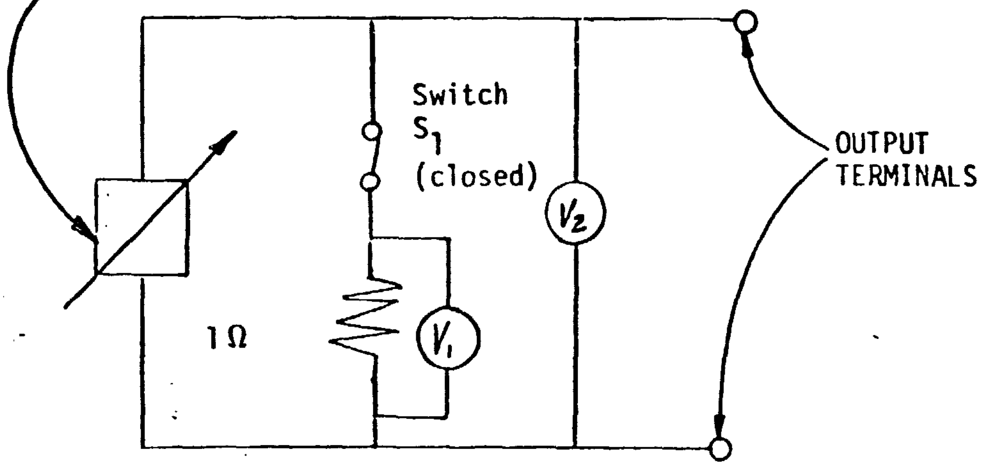
The modules were tested in accordance with JPL Low Cost Solar Array Project Document No. 5101-16, Revision A. A brief description of each test is as follows.

3.6.1 Thermal Cycling Test Procedure

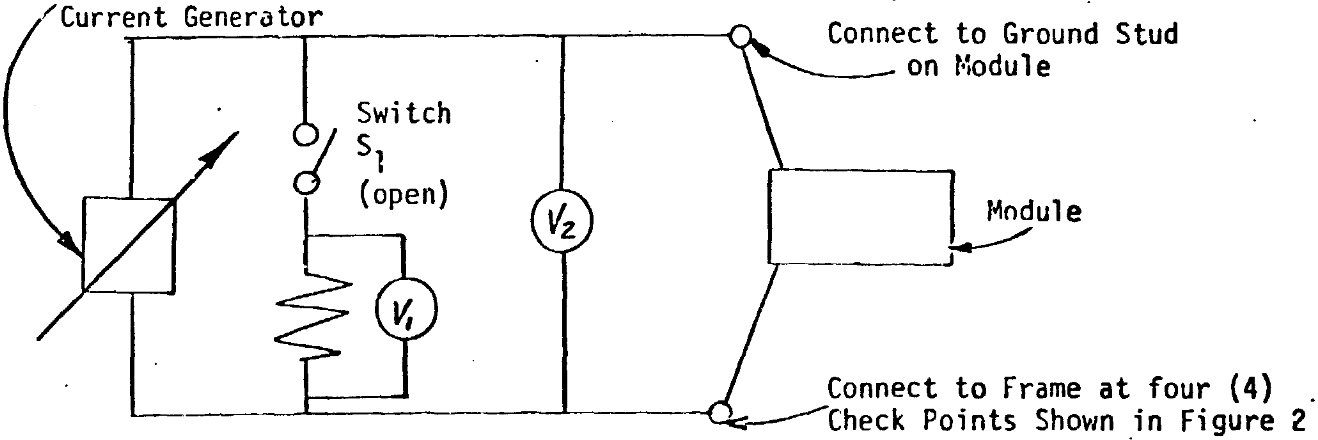
The modules were subjected to the thermal cycling procedure consisting of 50 cycles with the cell temperature varying between -40^{o}C and +90^{o}C. The temperature varied approximately linearly with time at a rate not exceeding 100^{o}C per hour and with a period not greater than 6 hours per cycle (from ambient to -40^{o}C to +90^{o}C to ambient). The modules circuitry was instrumented and monitored throughout the test to verify that no open circuits or short circuits occur during the exposure.

3.6.2 Humidity Test Procedure

The modules were subjected to humidity cycling at temperatures of 40.5^{o}C and relative humidity of 90% to 95%. The modules were tested in the open circuit condition, but with terminations protected from water



SCHEMATIC FOR CONSTANT CURRENT GENERATOR SETUP ADJUSTMENT



SCHEMATIC FOR ACTUAL MODULE GROUND CONTINUITY TESTING

FIGURE 1

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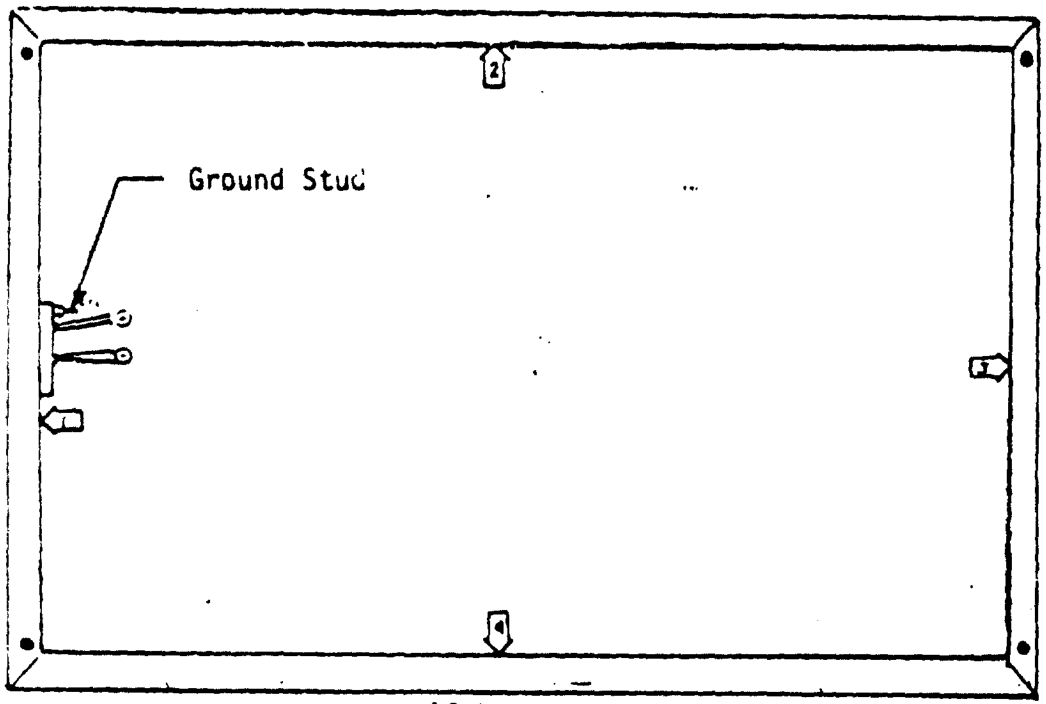
FIGURE 2



NOTE: For continuity check to insure proper grounding of frame members perform the following:

1. Connect one lead of the constant current generator to ground stud.
2. Touch the other lead to positions #1, #2, #3, and #4 as shown by arrows in diagram. Be sure to break through the anodize finish at these check points.
3. Read volt meter connected in the circuit. At 1 Amp current the acceptable voltage reading is $\leq$50 mV.

condensation. Electrical performance test was performed within one hour after removal from the humidity chamber.

3.6.3 Mechanical Cycling Test Procedure

The modules were subjected to a cyclic load test in which the module was supported only at the design support points and a uniform load normal to the module surface is cycled 10,000 times in an alternating negative and positive direction. Cycle rate did not exceed 20 cycles/minute. The module circuitry was instrumented to verify that no open circuitry or short circuits occur during the test. JPL Document 5101-19 "Cyclic Pressure-Load Developmental Testing of Solar Panels", February 1977, describes techniques suitable to the performance of this test.

3.6.4 Twisted Mounting Surface Test Procedure

The modules were subjected to a twist test by deflection of the substrate to which it is mounted. The deviation from a true flat surface during the test was ± 20 mm/m(± 1/4 inch per foot) measured along either mounting surface. The module circuitry was instrumented to verity that no open circuits or short circuits occur during the deflection test.

3.6.5 Hail Impact Test Procedure

The modules were subjected to normal impact loading with 20.0 mm (3/4 inch) diameter iceballs traveling at terminal velocity of 20.1 m/sec.(45 mph). At least three different points of impact were selected to include the test specimen's most sensitive exposed point, and each point was struck at least 3 times (a minimum of 9 impacts). The most senitive exposed point on a test specimen was determined experimentally through

destructive testing of a sample panel. Iceballs of 38 mm (1-1/2 in.) diameter were fired at candidate sensitive points with increasing velocity until the panel was broken.

The candidate points selected included the following:

1) Corners and edges of the modules.
2) Edges of cells, especially around electrical contacts.
3) Points of minimum spacing between cells.
4) Points of support for superstrate material
5) Points of maximum distance from points of support in (4) above.

Some scatter was expected in hitting a location on a module. Three repeated impacts were required to ensure that a sensitive point was struck. Error of up to 13 mm (1/2 in) in the location hit was acceptable. Iceball velocity at impact, was controlled to within ± 5 percent of terminal velocity for the required hailstone size. Iceballs were generally spherical in shape with a maximum deviation in diameter of ± 3 mm ($\pm$ 1/8 in). The iceballs were cooled to $-10^{\circ}C \pm 2^{\circ}C$ as measured in the compartment where they were stored. The modules were mounted in a manner representative of that used for actual installation of the module in the array. After each impact, the modules were inspected for evidence of visible damage.

3.6.6 Test Performance

The first six(6) modules tested at JPL experienced many cracked cell problems. The cracked cells in question have been reviewed by ASEC personnel. Many of the cracks were observed as terminated cracks within

the central portion of the cell. All of the cracks were, however, located either under or near the interconnection mesh. The size varies, but in general they were very narrow (approximately .0005" wide), and could not be seen without magnification. Only one module (No. 002) had any electrically degration, however. With only one open circuit (out of 12 modules or 1632 cells), it can be seen that the central contact pattern does insure good reliability even with some cracking in this area. In an effort to resolve the cracked cell problem, ASEC processed a few modules differently during the autoclave lamination process. We then selected one of these modules (Serial No. 011) and conducted our own thermal cycling per the JPL specification. After thirty (30) cycles, the module was removed from the chamber and inspected. A complete inspection, using a microscope and oil on the textured glass surface revealed no defects or changes. A verification of these results were made by JPL personnel who confirmed our findings. The module was then subjected to an additional twenty (20) cycles and reinspected at that time. The result after fifty (50) cycles was one cracked cell. This was in the form of a micro-crack from the center of the cell to one edge, and along the interconnect. This was the only change noted within the entire module. With the results of this testing, we felt contident that the problem was resolved. In addition to our testing, three (3) more modules (serial numbers 009, 010, and 013) that were processed the same as number 011 and tested at JPL. This testing further confirmed our results with very minor cell cracking. Because of these additional tests, it was determined that an acceptable solution was found and the tests were judged successful.

The only change between modules serial No.009,No.010,No.011 and No.013 and the earlier ones, was that the total thermal mass in the autoclave was

reduced in an effort to more closely match the bulk material and autoclave air temperature. Temperature was then monitored more closely before applying full pressure and vacuum. With our autoclave processing equipment, we monitor the air temperature outside the chamber. It is our feeling that with a full capacity load (entire autoclave filled with products), the thermal mass may be great enough so that the air temperature is actually higher than that of the materials (PVB, glass, cells, Tedlar, etc.). This being the case, the application of pressure and vacuum before reaching the correct material temperature, will cause excess stress along the interconnects and more than likely cause cell cracking. Another problem which can contribute to this, is that of the characteristics of the cell used in this module. We are using an aluminum back surface field cell which is generally a little more delicate.

4.1 Design Modifications

Some minor modifications were implemented during the pre-production phase of this contract. As discussed earlier, the module design was changed from (120) cells to (136) cells. This in turn generated all of the required updated paperwork, of which we will not go into detail. There were, however, a few modifications not generated by the increased number of cells. A modification was made to the output terminals that are encapsulated into the module. The original design used mesh, just like the interconnection between cells. It was found that this thin mesh did not withstand the handling that was required during module assembly. For this reason, the mesh was replaced by braded wire which was proven to be quite acceptable for this application. The slots in the end frame, which provide room for the output terminals to enter the junction box, were

increased in depth to insure ample room. Another modification to the frame was to move the mounting holes inward on the required 20mm increments. This provided sufficient room at the end of the corner lock brace (used to secure frame members together at the corners), to install a nut for mounting purposes. Simple modifications like these improved assembly, reliability, and production yield.

5.1 Recommendations

The overall design concept worked out quite well. As planned, the module assembly with the new interlocking spring clip corner assembly, was fast and easy to assemble.

5.2 Cells in Series

Due to the hotter than expected (NOCT) operating temperature, it would have been advantageous to have two (2) more cells to each series string. This would have made a total of thirty-six (36) in series, and would increase the quantity of cells to (144). The module as now designed, is very temperature sensitive. This is because of the fixed voltage requirement (15 Volts), and the fact that at this voltage, and NOCT, the power is no longer at the maximum power point. Since the power point is beyond the knee of the curve, current drops off very rapidly with a slight voltage (temperature) variation. The (36) cells in series would shift the curve back to the maximum power point area at NOCT. An alternate method of improvement would be to change Vno from 15 volts to 13.8 volts which allow maximum efficiency at the power point.

5.3 Packing Factor

The optimum packing density was achieved in this design using round cells. This design, especially after the redesign, (120 cells to 136 cells), created a rather low packing density (76.8%). A similar module using shaped cells (half-circle or semi-square) would have a better packing density and improved power-to-size ratio.

5.4 Cell Design

ASEC has produced a considerable number of cells using silicon with 1-3 ohm-cm resistivity and applying a back surface reflector only. The electrical performance of the 3" cells was comparable to that of the cell with a back surface field. In addition, the manufacturing cost is slightly lower. We would recommend this cell for future module production.

6.0 SUMMARY/ACCOMPLISHMENTS

Substantial information was gained during this contract. The redesign from (120) cells to (136) cells required considerable thought. The main restricting factors were the maximum physical size, size requirements within predetermined incremental dimensions, and the fixed voltage/power output at NOCT. We learned that our estimated NOCT figures were low with the result being a lower than expected (79 Watts/module average) power output. The frame design proved to be a major accomplishment with its ease of assembly and lack of external mechanical fasteners. The micro-cracks which developed in many cells during quality testing opened up a new area of concern. Because of this problem, considerable time was spent to analyze our procedures, our processes, and testing procedures. We did, however, determine a method

of overcoming these problems as mentioned earlier in the encapsulation section of this report. The diode protection across the output terminals proved to be quite satisfactory, and the mounting location inside the junction box also worked out well.

The design innovations and advancements over previous designs were primarly centered around the concept of higher volume, cost reduction, and future automation. The unique frame assembly was not only time saving, but can be easily automated for high volume production. White "Tedlar" was used for a backing which replaced the previously used clear Mylar that had to be painted white. The wire braid output terminals proved to be very durable and superior to the copper mesh method of connecting pigtail terminal leads. With the quantity of cells made during this contract, a good feeling for the economics of this kind of cell could be made. Overall, the module was easy to assemble and quite durable.

TABLE I

MODULE SERIAL NUMBER	TEST LOCATION AND TYPE OF LIGHT SOURCE	MODULE TEST TEMPERATURE	POWER AT 15V & NOCT (54.5°C)	TEST DATE	POWER AT 15V AND ESTIMATED NOCT (48°C)
001	JPL/Pulsed Xenon	28°C	------	10-12-79	80.3 W
001	JPL/Pulsed Xenon	28°C	------	10-22-79	81.8 W
001	Table Mt./Sunlight	16.8°C	------	12-13-79	91.4 W
001	Table Mt./Sunlight	30.3°C	------	12-13-79	90.7 W
001	JPL/Pulsed Xenon	22°C	74.6 W	10-22-79 (Data Corrected to 54.9°C)	
002	Table Mt./Sunlight	20.8°C	------	12-13-79	96.6 W
002	Table Mt./Sunlight	34.8°C	------	12-13-79	90.8 W
002	JPL/Pulsed Xenon	28°C	------	02-06-80	75.9 W
002	JPL/Pulsed Xenon	28°C	------	02-25-80	76.2 W
002	JPL/Pulsed Xenon	28°C	66.2 W	03-05-80	------
002	JPL/Pulsed Xenon	23°C	71.6 W	02-25-80(Corrected to 54.5°C)	
003	JPL/Pulsed Xenon	28°C	------	02-06-80	77.4 W
003	JPL/Pulsed Xenon	28°C	------	02-25-80	76.5 W
003	JPL/Pulsed Xenon	28°C	67.2 W	03-05-80	------
003	JPL/Pulsed Xenon	22°C	70.9 W	02-25-80 (Corrected to 54.5°C)	

TABLE I

MODULE SERIAL NUMBER	TEST LOCATION AND TYPE OF LIGHT SOURCE	MODULE TEST TEMPERATURE	POWER AT 15V & NOCT (54.5°C)	TEST DATE	POWER AT 15V AND ESTIMATED NOCT (48°C)
004	JPL/Pulsed Xenon	28°C	------	02-06-80	75.9 W
004	JPL/Pulsed Xenon	28°C	------	02-25-80	75.0 W
004	JPL/Pulsed Xenon	28°C	50.5 W	03-05-80	------
004	JPL/Pulsed Xenon	22°C	67.5 W	02-25-80	(Corrected to 54.5°C)
005	JPL/Pulsed Xenon	28°C	------	02-06-80	75.9 W
005	JPL/Pulsed Xenon	28°C	------	02-25-80	75.2 W
005	JPL/Pulsed Xenon	28°C	67.2 W	03-05-80	------
005	JPL/Pulsed Xenon	22°C	70.1W	02-25-80	(Corrected to 54.5°C)
006	JPL/Pulsed Xenon	28°C	------	02-06-80	73.6 W
006	JPL/Pulsed Xenon	28°C	------	02-25-80	72.0 W
006	JPL/Pulsed Xenon	28°C	67.1 W	03-05-80	------
006	JPL/Point-Xenon		77.95W		
006	JPL/Pulsed Xenon	22°C	64.1 W	02-25-80	(Corrected 54.5°C)

TABLE 2

MODULE SERIAL NUMBER	TEST LOCATION AND TYPE OF LIGHT SOURCE	MODULE TEST TEMPERATURE	POWER AT 15V & NOCT (54.5°C)	TEST DATE	POWER AT 15V AND ESTIMATED NOCT (48°C)
007	ASEC/Sunlight	35.5°C	81.9 W	03-17-80	------
008	ASEC/Sunlight	29.4°C	84.4 W	03-17-80	------
008	JPL/Point-Xenon		79.15 W		
009	ASEC/Sunlight	28.7°C	84.9 W	03-17-80	------
009	JPL/Point-Xenon		80.65 W		
C10	ASEC/Sunlight	23.4°C	81.7 W	05-02-80	------
010	JPL/Point-Xenon		78.85 W		

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MODULE SERIAL NUMBER	TEST LOCATION AND TYPE OF LIGHT SOURCE	MODULE TEST TEMPERATURE	POWER AT 15V & NOCT (54.5°C)	TEST DATE	POWER AT 15V AND ESTIMATED NOCT (48°C)
012	ASEC/Sunlight	26.2°C	31.7 W	05-02-80	------
012	JPL/Point-Xenon		79.15 W		
013	ASEC/Sunlight	31.8°C	80.3 W	06-04-80	------
013	JPL/Point-Xenon		76.90 W		